CHAPTER 5

OPEN CHANNELS

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Chapter Five - Open Channels

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5.1 Overview

5.1.1 Introduction

Consideration of open channel hydraulics is an integral part of projects in which artificial channels and improvements to natural channels are a primary concern. Open channels are encouraged for use, especially in the major drainage system, and can have advantages in terms of cost, capacity, multiple use (i.e., recreation, wildlife habitat, etc.), and flow routing storage. Disadvantages include right-of-way needs and maintenance requirements.

Where natural channels are not well defined, runoff flow paths can usually be determined and used as the basis for location and construction of channels. In some cases the well-planned use of natural channels and flow paths in the development of a major drainage system may obviate the need for an underground storm sewer system.

For any open channel conveyance, channel stability must be evaluated to determine what measures are needed so as to avoid bottom scour and bank cutting. This chapter emphasizes procedures for performing uniform flow calculations that aid in the selection or evaluation of appropriate channel linings, depths, and grades for natural or man-made channels. Allowable velocities are provided, along with procedures for evaluating channel capacity using Manning's equation.

Even where streams retains a relatively natural state, streambanks may need to be stabilized while vegetation recovers. To preserve riparian characteristics of channels, channel improvement or stabilization projects should minimize the use of visible concrete, riprap or other hard stabilization materials.

Hydraulic analysis software such as the Corps of Engineers HEC-RAS program may be useful when preparing preliminary and final channel designs.

For any open channel conveyance, channel stability must be evaluated to determine what measures are needed to avoid bottom scour and bank cutting. Channels shall be designed for long term stability, but be left in as near a natural condition as possible. The use of open, natural channels is especially encouraged in the major drainage system and can have advantages in terms of cost, capacity, multiple use (i.e., recreation, wildlife habitat, etc.) and flow routing storage. It shall be demonstrated that the natural condition or an alternative channel design will provide stable stream bed and bank conditions. Where this cannot be demonstrated, a concrete low flow liner with a nonerosive crossection may be required by the Director of Public Works and Utilities. Even where streams retain a relatively natural state, streambanks may need to be stabilized while vegetation recovers. To preserve riparian characteristics of channels, channel improvement or stabilization projects should minimize the use of visible concrete, riprap or other hard stabilization materials. The main classifications of open channel types are natural, bio-technical vegetated grass-lined, rock-lined, and concrete. Grass-lined channels include grass with mulch and/or sod, reinforced turf, and wetland bottom. Rock-lined channels include riprap, grouted riprap, and wire-enclosed rock.

Open channels shall be sized to handle the 100-year storm. Open channels shall be maintained by the developer or a property-owners' association unless an alternative ownership/maintenance arrangement has been approved by the Director of Public Works and Utilities, Planning Commission and the City Council.

5.1.2 Channel Types

The main classifications of open channel types are natural, bio-technical vegetated grass-lined, rock-lined, and concrete. Grass-lined channels include grass with mulch and/or sod, reinforced turf, and wetland bottom channel. Rock-lined channels include riprap, grouted riprap, and wire-enclosed rock. Concrete low flow liners are required, unless the engineer can clearly demonstrate an alternative channel design will provide stable stream bed and bank conditions.

5.1.2.1 Natural Channels

Natural channels are carved or shaped by nature prior to urbanization. Often, natural channels have mild slopes and are relatively stable. With increased flows due to urbanization, natural channels may experience erosion and may need grade control checks and localized bank protection to provide stabilization (UDFCD, 1990).

5.1.2.2 Grass-lined Channels

Grass-lined channels are the most desirable type of artificial channel. Vegetative linings stabilize the channel body, consolidate the soil mass of the bed, check erosion on the channel surface, and control the movement of soil particles along the channel bottom. Conditions under which vegetative linings may not be acceptable, however, include but are not limited to:

1. Flow conditions in excess of the maximum shear stress for bare soils,
2. Lack of the regular maintenance necessary to prevent domination by taller vegetation,

3. Lack of nutrients and inadequate topsoil,
4. Excessive shade,
5. High velocities, and
6. Right-of-way limitations

For grass-lined channels, proper seeding, mulching, and soil preparation are required during construction to assure establishment of a healthy stand of grass. Soil testing should be performed and the results evaluated by an agronomist to determine soil treatment requirements for pH, nitrogen, phosphorus, potassium, and other factors. In many cases, temporary erosion control measures are required to provide time for the seeding to establish a viable vegetative lining. Commercially available turf reinforcement products can be used to control erosion while vegetation is being established and to increase the erosion resistance of established vegetation.

Sodding, when implemented, should be staggered, to avoid seams in the direction of flow. Lapped or shingle sod should be staggered and overlapped by approximately 25 percent. Staked sod is usually only necessary for use on steeper slopes to prevent sliding. Low flow areas may need to be concrete or rock-lined to minimize erosion and maintenance problems.

Wetland bottom channels are a subset of grass-lined channels that are designed to encourage the development of wetlands and other riparian species in the channel bottom. In low flow areas, the banks may need protection against undermining (UDFCD, 1990).

5.1.2.3 Trickle Channel Linings

Under continuous baseflow conditions when a vegetative lining alone would not be appropriate, a small concrete pilot or trickle channel could be used to handle the continuous low flows. Vegetation could then be maintained for handling larger flows. The trickle channel allows for easier maintenance and reduces erosion caused by a meandering low flow channel. Sometimes rock-lined channels are used for trickle channels, but may require more maintenance and can encourage sediment deposition. Rock imbedded in concrete can obtain the best of both designs, but at greater cost. Trickle channel capacity should be roughly 1 to 5 percent of the design flow. Trickle flows may be conveyed in storm sewers (see Chapter 3).

5.1.2.4 Rock-lined Channels

Rock riprap, including clean rubble, is a common type of rock-lined channel. It presents a rough surface that can dissipate energy and mitigate increases in erosive velocity. These linings are usually less expensive than rigid concrete linings and have self-healing qualities that reduce maintenance. They typically require use of filter fabric and allow the infiltration and exfiltration of water. The growth of grass and weeds through the lining may present maintenance problems. The use of rock-lined channels may be restricted where right-of-way is limited, since the higher roughness values create larger cross sections. Wire-enclosed rock and grouted riprap are other examples of commonly used rock-lined channels

5.1.2.5 Concrete Channels

Concrete channels are used where smoothness offers a higher capacity for a given cross-sectional area. Higher velocities, however, create the potential for scour at channel lining transitions. A concrete lining can be destroyed by flow undercutting the lining, channel headcutting, or the buildup of hydrostatic pressure behind the rigid surfaces. Filter fabric may be required to prevent soil loss through pavement cracks. When properly designed, concrete linings may be appropriate where the channel width is restricted.

5.1.2.6 Maintenance

Open channels shall be maintained by the developer or a property-owners' association unless an alternative ownership/maintenance arrangement has been approved by the Director of Public Works and Utilities, Planning Commission and the City Council.

5.2 Symbols And Definitions

To provide consistency within this chapter, as well as throughout this manual, the following symbols will be used. These symbols were selected because of their wide use in open channel publications.

Table 5-1 Symbols And Definitions

Symbol	Definition	Units
A	Cross-sectional area	ft^2
b	Bottom width	ft
C_x	Correction factor	-
D	Depth of flow	ft
d_{avg}	Average flow depth in the main flow channel	ft
d_x	Diameter of stone for which x percent, by weight, of the gradation is finer	ft
Fr	Froude number	-
g	Acceleration of gravity	32.2 ft/s^2
h	Superelevation	ft
K_1	Correction term reflecting bank angle	-
L	Length of channel	ft
L_p	Length of downstream protection	ft
n	Manning's roughness coefficient	-
P	Wetted perimeter	ft
Q	Discharge rate	cfs
R	Hydraulic radius	ft
r_c	Mean radius of the bend	ft
S	Slope	ft/ft
S_f	Friction slope or energy grade line slope	ft/ft
SF	Stability factor	-
S_s	Specific gravity of the riprap material	lb/ft^2
Tw	Top width	ft
V or v	Velocity of flow	ft/s
W_{50}	Weight of the median particle	lb
y_c	Critical depth	ft
y_n	Normal depth	ft
Z	Critical flow section factor	-
θ	Bank angle with the horizontal	degrees
Φ	Riprap materials angle of repose	degrees

5.3 Hydraulic Terms

5.3.1 Introduction

An open channel is a channel or conduit in which water flows with a free surface. The hydraulics of an open channel can be very complex, encompassing many different flow conditions from steady-state uniform flow to unsteady, rapidly varied flow. Most of the problems in stormwater drainage involve uniform, gradually varied or rapidly varied flow states. The calculations for uniform and gradually varied flow are relatively straight forward and are based upon similar assumptions (e.g., parallel streamlines). Rapidly varied flow computations, such as hydraulic jumps and flow over spillways, however, can be very complex and the solutions are generally empirical in nature (Tulsa, 1993).

This section will present the basic equations and computational procedures for uniform, gradually varied, and rapidly varied flow. For more detailed discussion, the user is referred to references such as Chow's *Open-Channel Hydraulics* (1959) and French's *Open-Channel Hydraulics* (1985). Many proprietary and non-proprietary computer software packages are available that may be used to evaluate the hydraulics of open channels.

5.3.2 Steady And Unsteady Flow

Flow in open channels is classified as steady flow or unsteady flow. Steady flow occurs when discharge or rate of flow at any cross section is constant with time. In unsteady flow the discharge or rate of flow varies from one cross section to another, with time.

5.3.3 Uniform Flow And Normal Depth

Open channel flow is said to be uniform if the depth of flow is the same at every section. For a given channel geometry, roughness, slope, and discharge, there is only one possible depth for maintaining uniform flow. This depth is referred to as normal depth (Tulsa, 1993).

True uniform is difficult to observe in the field because not all of the parameters remain the same. However, channels are often designed assuming uniform flow. This approximation is generally adequate for drainage purposes. The engineer must be aware that uniform flow computation provides only an approximation of what will occur.

Manning's Equation, presented below, is recommended for evaluating uniform flow conditions in open channels.

$$Q = (1.49/n)\ A\ R^{2/3}\ S^{1/2} \qquad (5.1)$$

Where:
- Q = discharge rate for design conditions (cfs)
- n = Manning's roughness coefficient
- A = cross-sectional area (ft^2)
- R = hydraulic radius A/P (ft)
- P = wetted perimeter (ft)
- S = slope of the energy grade line (EGL) (ft/ft)

The Manning's n value is an important variable in open channel flow computations. Variation in this variable can significantly affect discharge, depth, and velocity estimates. Since Manning's n values depend on many different physical characteristics of natural and man-made channels, care and good engineering judgment must be exercised in the selection process.

For prismatic (e.g., trapezoid, rectangular) channels, in the absence of backwater conditions, the slope of the energy grade line, water surface and channel bottom are equal.

Since normal depth is computed so frequently, special tables and figures (see Table 5-2 and Figure 5-1) have been developed using the Manning's formula for various uniform cross sections to eliminate the need for trial and error solutions, which are time consuming. Table 5-2 is applicable only for trapezoidal channels.

5.3.3.1 Uniform Flow And Normal Depth Example

A trapezoidal channel has a bottom width of 8 feet and 4 to 1 side slopes. The grade is 0.005 feet per foot. Manning's n is 0.035. What is the normal depth for discharge of 100 cfs?

Solve using Table 5-2:

1. Calculate:

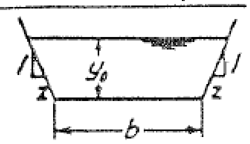
$$\frac{Q\,n}{b^{8/3}\,s_0^{1/2}} = \frac{100 \times 0.035}{8^{8/3} \times 0.005^{1/2}} = 0.19$$

2. From Table 5-2 with the above value of side slope horizontal dimension, z, equal to 4, it is found that:

$$\frac{y_0}{b} = 0.235\ ;\quad \textit{rearranging yields}\ \ y_0 = 0.235 \times b = 0.235 \times 8 = 1.88\ ft$$

The designer should be aware that as the roughness coefficient increases, the same discharge will flow at a greater depth. Conversely, flow at the computed depth will result in less discharge if the roughness coefficient increases

Uniform Flow in Trapezoidal Channels by Manning Formula



Values of $\frac{Qn}{b^{8/3}S_0^{1/2}}$

$\frac{y_0}{b}$	z = 0	z = 1/4	z = 1/2	z = 3/4	z = 1	z = 1 1/4	z = 1 1/2	z = 2	z = 2 1/2	z = 3	z = 4
0.02	0.00213	0.00215	0.00216	0.00217	0.00218	0.00219	0.00220	0.00221	0.00222	0.00223	0.00225
0.03	0.00414	0.00419	0.00423	0.00426	0.00429	0.00431	0.00433	0.00437	0.00440	0.00443	0.00449
0.04	0.00661	0.00670	0.00679	0.00685	0.00690	0.00696	0.00700	0.00707	0.00715	0.00722	0.00735
0.05	0.00947	0.00964	0.00980	0.00991	0.0100	0.0101	0.0102	0.0103	0.0104	0.0106	0.0109
0.06	0.0127	0.0130	0.0132	0.0134	0.0136	0.0137	0.0138	0.0141	0.0143	0.0145	0.0149
0.07	0.0162	0.0166	0.0170	0.0173	0.0176	0.0177	0.0180	0.0183	0.0186	0.0190	0.0196
0.08	0.0200	0.0206	0.0211	0.0215	0.0219	0.0222	0.0225	0.0231	0.0235	0.0240	0.0250
0.09	0.0240	0.0249	0.0256	0.0262	0.0267	0.0271	0.0275	0.0282	0.0289	0.0296	0.0310
0.10	0.0283	0.0294	0.0305	0.0311	0.0318	0.0324	0.0329	0.0339	0.0348	0.0358	0.0375
0.11	0.0329	0.0342	0.0354	0.0364	0.0373	0.0380	0.0387	0.0400	0.0413	0.0424	0.0448
0.12	0.0376	0.0393	0.0408	0.0420	0.0431	0.0441	0.0450	0.0466	0.0482	0.0497	0.0527
0.13	0.0425	0.0446	0.0464	0.0480	0.0493	0.0505	0.0516	0.0537	0.0556	0.0575	0.0613
0.14	0.0476	0.0501	0.0524	0.0542	0.0559	0.0573	0.0587	0.0612	0.0636	0.0659	0.0705
0.15	0.0528	0.0559	0.0585	0.0608	0.0628	0.0645	0.0662	0.0692	0.0721	0.0749	0.0805
0.16	0.0582	0.0619	0.0650	0.0676	0.0699	0.0720	0.0740	0.0776	0.0811	0.0845	0.0912
0.17	0.0638	0.0680	0.0717	0.0748	0.0775	0.0800	0.0823	0.0867	0.0907	0.0947	0.103
0.18	0.0695	0.0744	0.0786	0.0822	0.0854	0.0883	0.0910	0.0961	0.101	0.105	0.115
0.19	0.0753	0.0809	0.0857	0.0900	0.0936	0.0970	0.100	0.106	0.112	0.117	0.128
0.20	0.0813	0.0875	0.0932	0.0979	0.102	0.106	0.110	0.116	0.123	0.129	0.141
0.21	0.0873	0.0944	0.101	0.106	0.111	0.115	0.120	0.127	0.134	0.142	0.156
0.22	0.0935	0.101	0.109	0.115	0.120	0.125	0.130	0.139	0.147	0.155	0.171
0.23	0.0997	0.109	0.117	0.124	0.130	0.135	0.141	0.151	0.160	0.169	0.187
0.24	0.106	0.116	0.125	0.133	0.139	0.146	0.152	0.163	0.173	0.184	0.204
0.25	0.113	0.124	0.133	0.142	0.150	0.157	0.163	0.176	0.187	0.199	0.222
0.26	0.119	0.131	0.142	0.152	0.160	0.168	0.175	0.189	0.202	0.215	0.241
0.27	0.126	0.139	0.151	0.162	0.171	0.180	0.188	0.203	0.218	0.232	0.260
0.28	0.133	0.147	0.160	0.172	0.182	0.192	0.201	0.217	0.234	0.249	0.281
0.29	0.139	0.155	0.170	0.182	0.193	0.204	0.214	0.232	0.250	0.267	0.302
0.30	0.146	0.163	0.179	0.193	0.205	0.217	0.227	0.248	0.267	0.286	0.324
0.31	0.153	0.172	0.189	0.204	0.217	0.230	0.242	0.264	0.285	0.306	0.347
0.32	0.160	0.180	0.199	0.215	0.230	0.243	0.256	0.281	0.304	0.327	0.371
0.33	0.167	0.189	0.209	0.227	0.243	0.257	0.271	0.298	0.323	0.348	0.396
0.34	0.174	0.198	0.219	0.238	0.256	0.272	0.287	0.315	0.343	0.369	0.422
0.35	0.181	0.207	0.230	0.251	0.270	0.287	0.303	0.334	0.363	0.392	0.450
0.36	0.190	0.216	0.241	0.263	0.283	0.302	0.319	0.353	0.384	0.416	0.477
0.37	0.196	0.225	0.251	0.275	0.297	0.317	0.336	0.372	0.406	0.440	0.507
0.38	0.203	0.234	0.263	0.289	0.311	0.333	0.354	0.392	0.429	0.465	0.536
0.39	0.210	0.244	0.274	0.301	0.326	0.349	0.371	0.412	0.452	0.491	0.568
0.40	0.218	0.254	0.286	0.314	0.341	0.366	0.389	0.433	0.476	0.518	0.600
0.41	0.225	0.263	0.297	0.328	0.357	0.383	0.408	0.455	0.501	0.545	0.634
0.42	0.233	0.279	0.310	0.342	0.373	0.401	0.427	0.478	0.526	0.574	0.668
0.43	0.241	0.282	0.321	0.356	0.389	0.418	0.447	0.501	0.553	0.604	0.703
0.44	0.249	0.292	0.334	0.371	0.405	0.437	0.467	0.524	0.579	0.634	0.739
0.45	0.256	0.303	0.346	0.385	0.422	0.455	0.487	0.548	0.607	0.665	0.778
0.46	0.263	0.313	0.359	0.401	0.439	0.475	0.509	0.574	0.635	0.696	0.816
0.47	0.271	0.323	0.371	0.417	0.457	0.494	0.530	0.600	0.665	0.729	0.856
0.48	0.279	0.333	0.384	0.432	0.475	0.514	0.552	0.626	0.695	0.763	0.897
0.49	0.287	0.345	0.398	0.448	0.492	0.534	0.575	0.652	0.725	0.797	0.939
0.50	0.295	0.356	0.411	0.463	0.512	0.556	0.599	0.679	0.758	0.833	0.983
0.52	0.310	0.377	0.438	0.496	0.548	0.599	0.646	0.735	0.820	0.906	1.07
0.54	0.327	0.398	0.468	0.530	0.590	0.644	0.696	0.795	0.891	0.984	1.17
0.56	0.343	0.421	0.496	0.567	0.631	0.690	0.748	0.856	0.963	1.07	1.27
0.58	0.359	0.444	0.526	0.601	0.671	0.739	0.802	0.922	1.04	1.15	1.37
0.60	0.375	0.468	0.556	0.640	0.717	0.789	0.858	0.988	1.12	1.24	1.49
0.62	0.391	0.492	0.590	0.679	0.763	0.841	0.917	1.06	1.20	1.33	1.60
0.64	0.408	0.516	0.620	0.718	0.809	0.894	0.976	1.13	1.28	1.43	1.72

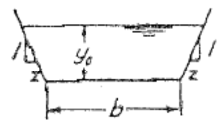
Table 5-2 Uniform Flow for Trapezoidal Channels by Manning Formula

Source: UDFCD, 1990

NORMAL DEPTH FOR UNIFORM FLOW $\frac{y_0}{b}$ = 0.66 to 5.00 (4)

UNIFORM FLOW IN TRAPEZOIDAL CHANNELS BY MANNING FORMULA

Values of $\frac{Qn}{b^{8/3}S_0^{1/2}}$



$\frac{y_0}{b}$	z = 0	z = $\frac{1}{4}$	z = $\frac{1}{2}$	z = $\frac{3}{4}$	z = 1	z = $1\frac{1}{4}$	z = $1\frac{1}{2}$	z = 2	z = $2\frac{1}{2}$	z = 3	z = 4
0.66	0.424	0.541	0.653	0.759	0.858	0.951	1.04	1.21	1.37	1.53	1.85
0.68	0.441	0.566	0.687	0.801	0.908	1.01	1.10	1.29	1.47	1.64	1.98
0.70	0.457	0.591	0.722	0.842	0.958	1.07	1.17	1.37	1.56	1.75	2.12
0.72	0.474	0.617	0.757	0.887	1.01	1.13	1.24	1.45	1.66	1.87	2.27
0.74	0.491	0.644	0.793	0.932	1.07	1.19	1.31	1.55	1.77	1.98	2.41
0.76	0.508	0.670	0.830	0.981	1.12	1.26	1.39	1.64	1.88	2.11	2.57
0.78	0.525	0.698	0.868	1.03	1.18	1.32	1.46	1.73	1.98	2.24	2.73
0.80	0.542	0.725	0.906	1.08	1.24	1.40	1.54	1.83	2.10	2.37	2.90
0.82	0.559	0.753	0.945	1.13	1.30	1.47	1.63	1.93	2.22	2.51	3.07
0.84	0.576	0.782	0.985	1.18	1.36	1.54	1.71	2.03	2.34	2.65	3.25
0.86	0.593	0.810	1.03	1.23	1.43	1.61	1.79	2.14	2.47	2.80	3.44
0.88	0.610	0.839	1.07	1.29	1.49	1.69	1.88	2.25	2.60	2.95	3.63
0.90	0.627	0.871	1.11	1.34	1.56	1.77	1.98	2.36	2.74	3.11	3.83
0.92	0.645	0.898	1.15	1.40	1.63	1.86	2.07	2.48	2.88	3.27	4.04
0.94	0.662	0.928	1.20	1.46	1.70	1.94	2.16	2.60	3.03	3.43	4.25
0.96	0.680	0.960	1.25	1.52	1.78	2.03	2.27	2.73	3.17	3.61	4.48
0.98	0.697	0.991	1.29	1.58	1.85	2.11	2.37	2.85	3.33	3.79	4.70
1.00	0.714	1.02	1.33	1.64	1.93	2.21	2.47	2.99	3.48	3.97	4.93
1.05	0.759	1.10	1.46	1.80	2.13	2.44	2.75	3.33	3.90	4.45	5.55
1.10	0.802	1.19	1.58	1.97	2.34	2.69	3.04	3.70	4.34	4.96	6.21
1.15	0.846	1.27	1.71	2.14	2.56	2.96	3.34	4.09	4.82	5.52	6.91
1.20	0.891	1.36	1.85	2.33	2.79	3.24	3.68	4.50	5.32	6.11	7.68
1.25	0.936	1.45	1.99	2.52	3.04	3.54	4.03	4.95	5.86	6.73	8.48
1.30	0.980	1.54	2.14	2.73	3.30	3.85	4.39	5.42	6.42	7.39	9.34
1.35	1.02	1.64	2.29	2.94	3.57	4.18	4.76	5.90	7.01	8.10	10.2
1.40	1.07	1.74	2.45	3.16	3.85	4.52	5.18	6.43	7.65	8.83	11.2
1.45	1.11	1.84	2.61	3.39	4.15	4.88	5.60	6.98	8.30	9.62	12.2
1.50	1.16	1.94	2.78	3.63	4.46	5.26	6.04	7.55	9.02	10.4	13.3
1.55	1.20	2.05	2.96	3.88	4.78	5.65	6.50	8.14	9.74	11.3	14.4
1.60	1.25	2.15	3.14	4.14	5.12	6.06	6.99	8.79	10.5	12.2	15.6
1.65	1.30	2.27	3.33	4.41	5.47	6.49	7.50	9.42	11.3	13.2	16.8
1.70	1.34	2.38	3.52	4.69	5.83	6.94	8.02	10.1	12.2	14.2	18.1
1.75	1.39	2.50	3.73	4.98	6.21	7.41	8.57	10.9	13.0	15.2	19.5
1.80	1.43	2.62	3.93	5.28	6.60	7.89	9.13	11.6	14.0	16.3	20.9
1.85	1.48	2.74	4.15	5.50	7.01	8.40	9.75	12.4	15.0	17.4	22.4
1.90	1.52	2.86	4.36	5.91	7.43	8.91	10.4	13.2	15.9	18.7	24.0
1.95	1.57	2.99	4.59	6.24	7.87	9.46	11.0	14.0	17.0	19.9	25.6
2.00	1.61	3.12	4.83	6.58	8.32	10.0	11.7	14.9	18.0	21.1	27.2
2.10	1.71	3.39	5.31	7.30	9.27	11.2	13.1	16.8	20.3	23.9	30.8
2.20	1.79	3.67	5.82	8.06	10.3	12.5	14.6	18.7	22.8	26.8	34.7
2.30	1.89	3.96	6.36	8.86	11.3	13.8	16.2	20.9	25.4	30.0	38.8
2.40	1.98	4.26	6.93	9.72	12.5	15.3	17.9	23.1	28.3	33.4	43.3
2.50	2.07	4.58	7.52	10.6	13.7	16.8	19.8	25.6	31.3	37.0	48.0
2.60	2.16	4.90	8.14	11.6	15.0	18.4	21.7	28.2	34.5	40.8	53.0
2.70	2.26	5.24	8.80	12.6	16.3	20.1	23.8	31.0	37.9	44.8	58.4
2.80	2.35	5.59	9.49	13.6	17.8	21.9	25.9	33.8	41.6	49.1	64.0
2.90	2.44	5.95	10.2	14.7	19.3	23.8	28.2	36.9	45.3	53.7	70.1
3.00	2.53	6.33	11.0	15.9	20.9	25.8	30.6	40.1	49.4	58.4	76.4
3.20	2.72	7.12	12.5	18.3	24.2	30.1	35.8	47.1	58.0	68.9	90.3
3.40	2.90	7.97	14.2	21.0	27.9	34.8	41.5	54.6	67.7	80.2	105
3.60	3.09	8.86	16.1	24.0	32.0	39.9	47.8	63.0	78.2	92.8	122
3.80	3.28	9.81	18.1	27.1	36.3	45.5	54.6	72.4	89.6	107	141
4.00	3.46	10.8	20.2	30.5	41.1	51.6	61.9	82.2	102	122	160
4.50	3.92	13.5	26.2	40.1	54.5	68.8	82.9	111	136	164	217
5.00	4.39	16.7	33.1	51.5	70.3	89.2	108	145	181	216	287

Table 5-2 (continued) Uniform Flow for Trapezoidal Channels by Manning Formula

Source: UDFCD, 1990

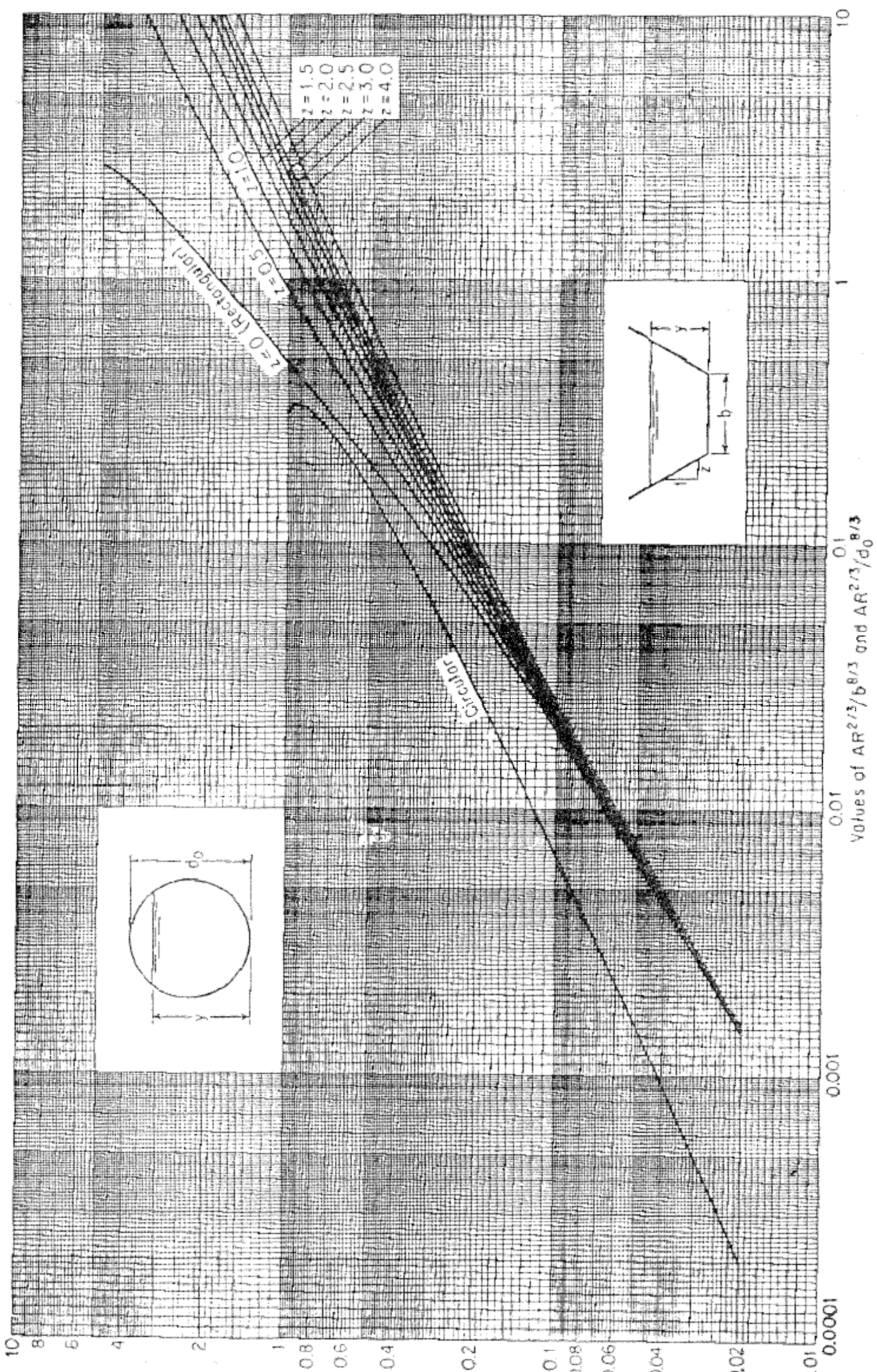


Figure 5-1 Normal Depth for Uniform Flow in Open Channels

Source: Chow, 1959

5.3.4 Critical Flow

Critical flow in an open channel or covered conduit with a free water surface is characterized by the following conditions:

- The specific energy is a minimum for a given discharge.
- The discharge is a maximum for a given specific energy.
- The specific force is a minimum for a given discharge.
- The velocity head is equal to half the hydraulic depth in a channel of small slope.
- The Froude number is equal to 1.0.
- The velocity of flow in a channel of small slope is equal to the celerity of small gravity waves in shallow waters.

If the critical state of flow exists throughout an entire reach, the channel flow is critical and the channel slope is at critical slope S_c. A slope less than S_c will cause subcritical flow, while a slope greater than S_c will cause supercritical flow. Under subcritical flow, surface waves propagate upstream as well as downstream, and control of subcritical flow depth is always downstream. Under supercritical flow, surface disturbance can propagate only in the downstream direction, and control of supercritical flow depth is always at the upstream end of the critical flow region. A flow at or near the critical state is not stable. In design, if the depth is found to be at or near critical, the shape or slope should be changed to achieve greater hydraulic stability.

The criteria of minimum specific energy for critical flow results in the definition of the Froude number, which is expressed by the following equation:

$$Fr = v / (gD)^{0.5} \tag{5.2}$$

Where:

Fr	=	Froude number
v	=	mean velocity of flow (ft/s)
g	=	acceleration of gravity (32.2 ft/s^2)
D	=	hydraulic depth (ft) - defined as the cross sectional area of water normal to the direction of channel flow divided by free surface width.

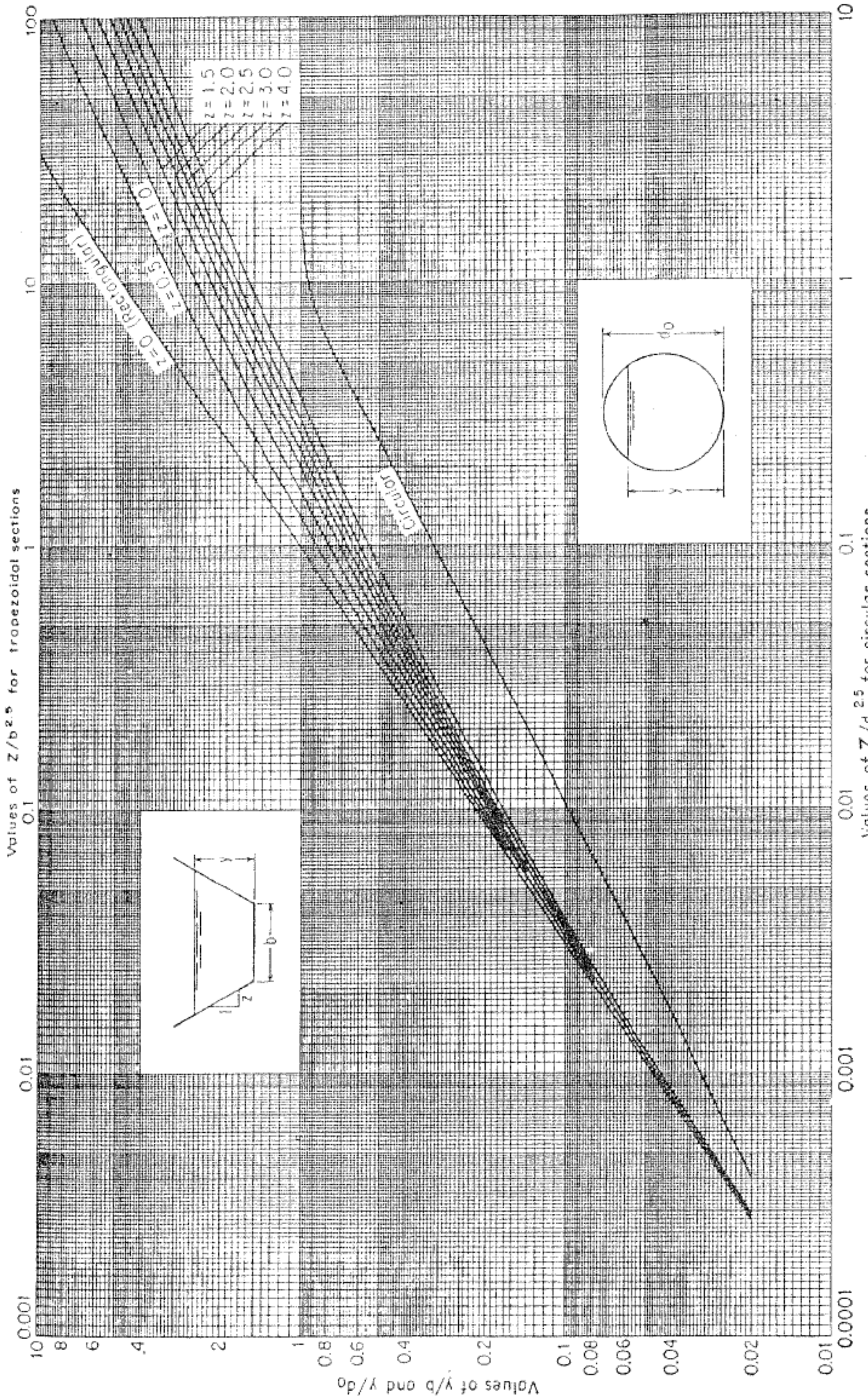
Since the Froude number is a function of depth, the equation indicates there is only one possible critical depth for maintaining a given discharge in a given channel. When the Froude number equals 1.0, the flow is critical. The Froude number should be calculated for the design of open channels to check the flow state. The computation of critical flow for trapezoidal and circular sections can be performed with the use of Figure 5-2 (Chow, 1959).

5.3.5 Gradually Varied Flow

The most common occurrence of gradually varied flow in storm drainage is the backwater created by culverts, storm sewer inlets, or channel constrictions. For these conditions, the flow depth will be greater than normal depth in the channel and the water surface profile should be computed using backwater techniques.

Many computer programs are available for computation of backwater curves. The most general and widely used program is, HEC-RAS, River Analysis System, developed by the U.S. Army Corps of Engineers (USACE, 1995) and is the program recommended for floodwater profile computations. HEC-RAS will compute water surface profiles for natural and man-made channels. Bridge Waterways Analysis Model (WSPRO) and HY-8 are programs developed for the Federal Highway Administration that can also be used to perform backwater calculations for both natural and artificial channels.

For prismatic channels, the backwater calculation can be computed manually using the direct step method, as presented by Chow (1959). For an irregular nonuniform channel, the standard step method is recommended, although it is a more tedious and iterative process. The use of HEC-RAS is recommended for non-uniform channel analysis. The reader is directed to the HEC-RAS documentation for proper use of the model.



NOTE: $Z = Q/\sqrt{g}$

Figure 5-2 Critical Depth in Open Channels

Source: Chow, 1959

5.3.6 Rapidly Varied Flow

Rapidly varied flow is characterized by pronounced curvature of streamlines. The change in curvature may become so abrupt that the flow profile is virtually broken, resulting in high turbulence. Empirical solutions are usually relied on to solve specific, rapidly varying flow problems. Hydraulic jump is an example of rapidly varied flow that commonly occurs in urban storm drainage.

5.3.6.1 Hydraulic Jump

Hydraulic jumps occur when a supercritical flow rapidly changes to subcritical flow. The result is usually an abrupt rise of the water surface with an accompanying loss of kinetic energy. The hydraulic jump is an effective energy dissipation device which is often used to control erosion at drainage structures.

In urban hydraulics, the jump may occur at grade control structures, inside of or at the outlet of storm sewers or concrete box culverts, or at the outlet of an emergency spillway for detention ponds. The evaluation of a hydraulic jump should consider the high energy loss and erosive forces that are associated with the jump. For rigid-lined facilities such as pipes or concrete channels, the forces and the change in energy can affect the structural stability or the hydraulic capacity. For grass-lined channels, unless the erosive forces are controlled, serious damage can result. Control of jump location is usually obtained by check dams or grade control structures that confine the erosive forces to a protected area. Flexible material such as riprap or rubble usually affords the most effective protection.

5.3.6.1.1 Storm Sewers

The analysis of the hydraulic jump inside storm sewers is approximate, because of the lack of data for circular, elliptical, or arch sections. The jump can be approximately located by intersecting the energy grade line of the supercritical and subcritical flow reaches. The primary concerns are whether the pipe can withstand the forces which may separate the joint or damage the pipe wall, and whether the jump will affect the hydraulic characteristics. The effect on pipe capacity can be determined by evaluating the energy grade line, taking into account the energy lost by the jump. In general, for Froude numbers less than 2.0, the loss of energy is less than 10 percent. French (1985) provides semi-empirical procedures to evaluate the hydraulic jump in circular and other non-rectangular channel sections. "Hydraulic Analysis of Broken Back Culverts", Nebraska Department of Roads, January 1998 provides guidance for analysis of hydraulic jump in pipes.

5.3.6.1.2 Box Culverts

For long box culverts with a concrete bottom, the concerns about jump are the same as for storm sewers. However, the jump can be adequately defined for box culverts/drains and for spillways using the jump characteristics of rectangular sections. The relationship between variables for a hydraulic jump in rectangular sections can be expressed as:

$$D_2 = -(D_1/2) + [(D_1^2/4) + (2v_1^2D_1/g)]^{1/2} \tag{5.3}$$

Where:

D_2 = depth below jump (ft)
D_1 = depth above jump (ft)
v_1 = velocity above jump (ft/s)
g = acceleration due to gravity (32.2 ft/s^2)

Additional details on hydraulic jumps can be found in HEC-14 (1983), Chow (1959), Peterska (1978), and French (1985).

5.3.6.1.3 Vertical Drop Structures

Chow (1959) used experimental data to determine hydraulic jump conditions at vertical drop structures. The aerated free-falling nappe in a vertical check drop structure will reverse the curvature and turn smoothly into supercritical flow on the apron, which may form a hydraulic jump downstream. Based on the relationships developed by Chow, the length of the hydraulic jump can be determined. A good approximation of the hydraulic jump length is six times the sequent depth (UDFCD, 1990). The reader is referred to Chow for a more detailed presentation.

5.4 General Open Channel Design Criteria

5.4.1 Introduction

In general, the following criteria should be used for open channel design:

1. Trapezoidal cross sections are preferred and triangular shapes should be avoided.

2. Channel side slopes shall be stable throughout the entire length and side slope shall depend on the channel material. A maximum of 4H:1V is recommended for vegetation and 2H:1V for riprap, unless otherwise justified by calculations.

3. If relocation of a stream channel is unavoidable, the cross-sectional shape, meander, pattern, roughness, sediment transport, and slope should generally conform to the existing conditions insofar as practicable, after giving consideration to increased flows from urbanization. Energy dissipation may be necessary.

4. Streambank stabilization should be provided, when appropriate, as a result of any stream disturbance such as encroachment and should include both upstream and downstream banks as well as the local site.

5. A low flow or trickle channel is recommended for all grass-lined channels.

6. Low flow sections shall be used in the design of channels with large cross sections.

7. New channels with bottom widths greater than 10 feet shall be designed with a minimum bottom cross slope of 12 to 1 to discourage meandering.

8. Superelevation of the water surface at horizontal curves shall be accounted for by increased freeboard.

9. Computation of water surface profiles shall be presented for all open channels utilizing standard backwater methods, taking into consideration losses due to changes in velocity, drops, and obstructions. The hydraulic and energy grade lines shall also be shown on preliminary and construction drawings. When potential erosion and flood capacity problems are identified, modifications to the channel may be necessary (Tulsa 1993).

5.4.2 Channel Transitions

The following criteria should be considered at channel transitions:

1. Transition to channel sections should be smooth and gradual.

2. A straight line connecting flow lines at the two ends of the transition should not make an angle greater than 12.5 degrees with the axis of the main channel.

3. Transition sections should be designed to provide a gradual transition to avoid turbulence and eddies.
4. Energy losses in transitions should be accounted for as part of the water surface profile calculations.

5. Scour downstream from rigid-to-natural and steep-to-mild slope transition sections should be accounted for through velocity-slowing and energy-dissipating devices.

5.4.3 Return Period Design Criteria

Open channels shall be sized to handle the 100-year storm.

When comprising the minor drainage system, open channels shall be sized to handle the 5-year storm in residential areas and the 10-year storm in downtown areas and industrial/commercial developments. For major drainage systems, open channels shall be sized to handle the 100-year storm.

5.4.3.1 Approximate Flood Limits Determination

Refer to Section 1.5.6 Flood Corridor Management for guidance on policy requirements for flood limit determination. For cases when the design engineer can demonstrate that a complete backwater analysis is unwarranted, approximate methods may be used.

A generally accepted method for approximating the 100-year flood elevation is outlined as follows:

1. Divide the stream or tributary into reaches that may be approximated using average slopes, cross sections, and roughness coefficients for each reach.

2. Estimate the 100-year peak discharge for each reach using the appropriate hydrologic method.

3. Compute normal depth for uniform flow in each reach using Manning's equation for the reach characteristics from Step 1 and peak discharge from Step 2.

4. Use the normal depths computed in Step 3 to approximate the 100-year flood elevation in each reach. The 100-year flood elevation is then used to delineate the floodplain.

This approximate method is based on several assumptions, including, but not limited to, the following:

1. A channel reach is accurately approximated by average characteristics throughout its length.

2. The cross-sectional geometry, including area, wetted perimeter, and hydraulic radius, of a reach may be approximated using typical geometric properties that can be used in Manning's equation to solve for normal depth.

3. Uniform flow can be established and backwater effects are negligible between reaches.

4. Expansion and contraction effects are negligible.

As indicated, the approximate method is based on a number of restrictive assumptions that may limit the accuracy of the approximation and applicability of the method. The engineer is responsible for appropriate application of this method to get reliable results.

Where a complete backwater analysis is warranted, the engineer is encouraged to use the USACE HEC-RAS model.

5.4.4 Velocity Limitations

Sediment transport requirements must be considered for conditions of flow below the design frequency, minimum channel flow velocity for the 2-year storm shall be 2.0 feet per second. A low flow channel component within a larger channel can reduce maintenance by improving sediment transport in the channel. Channel flow velocities shall be non erosive for the 2-, 10- and 100-year storms. Trickle channel design flow rate shall be 1% of the major storm flow rate and shall be non erosive. Grade control structures, streambank protection, and construction and maintenance considerations shall be determined during design.

The final design of artificial open channels should be consistent with the velocity limitations for the selected channel lining. Maximum velocity values for selected lining categories are presented in Table 5-3. Velocity limitations for established vegetative linings are reported in Table 5-4.

Table 5-3 Maximum Design Velocities for Comparing Lining Materials (all values in feet per second)

Material	Clear Water	Water with Colloidal Silt	Water with Non-colloidal Silt, Sand or Gravel
Fine Sand (colloidal)	1.5	2.5	1.5
Sand Loam (noncolloidal)	1.45	2.5	2.0
Silt Loam (noncolloidal)	2.0	3.0	2.0
Alluvial Silt (noncolloidal)	2.0	3.5	2.0
Alluvial Silt (colloidal)	3.75	5.0	3.0
Firm Loam	2.5	3.5	2.25
Fine Gravel	2.5	5.0	3.75
Stiff Clay (very colloidal)	3.75	5.0	3.0
Graded Loam to Cobbles(noncol)	3.75	5.0	5.0
Graded Silt to Cobbles (colloidal)	3.75	5.0	3.0
Coarse Gravel	4.0	6.0	6.5
Cobbles and Shingles	5.0	5.5	6.5
Shales and Hard Pans	6.0	6.0	5.0

Source: Fortier and Scoby, 1926.

Table 5-4 Maximum Velocities For Vegetative Channel Linings

Vegetation Type	Slope Range (%)[1]	Maximum Velocity[2] (ft/s)	
		Erosion Resistant Soils	Easily Eroded Soils
Bermuda grass	0-5	8	6
	5-10	7	5
	>10	6	4
Kentucky bluegrass	0-5	7	5
Buffalo grass	5-10	6	4
	>10	5	3
Grass mixture	0-5[1]	5	4
	5-10	4	3
Kudzu, alfalfa	0-5[3]	3.5	2.5
Annuals	0-5	3.5	2.5
Sod		4.0	4.0
Lapped sod		5.5	5.5

Source: USDA, TP-61, 1954.

[1] Do not use on slopes steeper than 10 percent except for side-slope in combination channel.

[2] Use velocities exceeding 5 ft/s only where good stands can be established and maintained.

[3] Do not use on slopes steeper than 5 percent except for side-slope in combination channel.

5.4.5 Grade Control Structures

Grade control structures are used to prevent streambed degradation. This is accomplished in two ways. First, the structures provide local base levels that prevent bed erosion and subsequent slope increases. Second, some structures provide controlled dissipation of energy between upstream and downstream sides of the structure. Structure choice depends on existing or anticipated erosion, cost, and environmental objectives. Design guidance for grade control structures is provided in Section 5.10. Additional guidance can be found in the National Engineering Handbook, Section 11, Drop Spillways and Section 14, Chute Spillways.

Examples of grade control structures include:

Sills or Check Structures - A sill is a structure that extends across a channel and has a surface that is flush with the channel invert or that extends a foot or two above the invert. Because sills are intended to prevent scouring of the bed, they should be placed close enough together to control the energy grade line and prevent scour between structures. Sills may be notched at the lowest flow point location to concentrate low flows to improve aquatic habitat and water quality or for aesthetic reasons. In highly visible locations, sills extending above the channel invert may be constructed of, or faced with, materials such as natural stone that create an attractive appearance. Sills may also be modified to allow for passage of boats or fish, if desired.

Drop Structures, Chutes, and Flumes - Drop structures provide for a vertical drop in the channel invert between the upstream and downstream sides, whereas chutes and flumes provide for a more gradual change in invert elevation. Because of the high energies that must be dissipated, pre-formed scour holes or plunge pools are required below these structures.

The design of hydraulic structures, such as drop structures, must consider safety of the general public, especially when multiple uses are allowed (i.e., boating and fishing). There are certain hazards that can be associated with drop structures, such as the “reverse roller” phenomenon which can trap an individual and result in drowning. As a result, it may be necessary to sign locations accessible by the public to warn of the danger associated with the hydraulic structure.

5.4.6 Streambank Protection

Streambanks subject to erosion are protected by stabilizing eroding soils, planting vegetation, covering the banks with various materials, or building structures to deflect stream currents away from the bank. Placement and type of bank protection vary, depending on the cause of erosion, environmental objectives, and cost. Section 5-11 identifies different streambank protection measures that are recommended for bank stability.

5.4.7 Construction And Maintenance Considerations

Open channels shall be maintained by the developer or a property-owners’ association unless an alternative ownership/maintenance arrangement has been approved by the Director of Public Works and Utilities, Planning Commission and the City Council.

An important step in the design process involves identifying whether special provisions are warranted to properly construct or maintain proposed facilities.

Open channels can lose hydraulic capacity without adequate maintenance. Maintenance may include repairing erosion damage, mowing grass, cutting brush, and removing sediment or debris. Brush, sediment, or debris can reduce design capacity and can harm or kill vegetative linings, thus creating the potential for erosion damage during large storm events. Maintenance of vegetation should include mowing, the appropriate application of fertilizer, irrigation during dry periods, and reseeding or resodding to restore the viability of damaged areas. Extra sizing may be used to account for future vegetation growth.

Implementation of a successful maintenance program is directly related to the accessibility of the channel system and the easements necessary for maintenance activities. The easement cross-section must accommodate the depth and width of flow from the 100-year storm. The width must also be designed to allow for access of maintenance equipment.

5.5 Natural Channel Design Criteria

Natural channels in the Lincoln area are sometimes found to have erodible banks and bottoms which tend to result in steep vertical banks. Other channels may have mild slopes and are reasonably stable. If natural channels are to be used in urbanized and to-be-urbanized areas to convey stormwater runoff, it can be assumed that there will be increased flow peaks and volumes that will result in increased channel erosion. As such, an hydraulic analysis during the planning and design phase is necessary to address the potential for erosion, and will usually result in the need for some stabilization measures.

The following criteria and analysis techniques are recommended for natural channel evaluation and stabilization:

- The channel and over-bank areas must have adequate capacity for the 100-year post-development storm runoff.
- The water surface profiles must be defined and delineated so that the 100-year floodplain can be identified and managed. Plan and profile drawings should be prepared of the FEMA floodplain, and allowances should be made for future bridges or culverts.
- Filling of the floodplain is subject to the restriction of floodplain regulations.
- Manning's n roughness factors representative of maintained channel conditions should be used. Table 5-5 provides representative values of the roughness factor in natural streams.
- Erosion control structures such as drop structures and grade control checks should be provided as necessary to control flow velocities and channel erosion.

Table 5-5 Uniform Flow Values Of Roughness Coefficient - n

Type Of Channel And Description	Minimum	Normal	Maximum
Minor streams (top width at flood stage < 100 ft)			
a. Streams on Plain			
1. Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
2. Same as above, but more stones and weeds	0.030	0.035	0.040
3. Clean, winding, some pools and shoals	0.033	0.040	0.045
4. Same as above, but some weeds and some stones	0.035	0.045	0.050
5. Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
6. Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
Floodplains			
a. Pasture, no brush			
1. Short grass	0.025	0.030	0.035
2. High grass	0.030	0.035	0.050
b. Cultivated area			
1. No crop	0.020	0.030	0.040
2. Mature row crops	0.025	0.035	0.045
3. Mature field crops	0.030	0.040	0.050
c. Brush			
1. Scattered brush, heavy weeds	0.035	0.050	0.070
2. Light brush and trees	0.040	0.060	0.080
3. Medium to dense brush	0.070	0.100	0.160

Table 5-5 (continued) Uniform Flow Values Of Roughness Coefficient - n

d. Trees			
1. Dense willows, straight	0.110	0.150	0.200
2. Cleared land, tree stumps, no sprouts	0.030	0.040	0.050
3. Same as above, but with heavy growth of sprouts	0.050	0.060	0.080
4. Heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
5. Same as above, but with flood stage reaching branches	0.100	0.120	0.160
Major Streams (top width at flood stage > 100 ft).			
a. Regular section with no boulders or brush	0.025	.....	0.060
b. Irregular and rough section	0.035	.....	0.100

Natural channels should be left in as near a natural condition as feasible. However, with most natural channels, grade control structures will need to be constructed at regular intervals to limit channel degradation and to maintain what is expected to be the final stable longitudinal slope after full urbanization of the watershed. In addition, the engineer is reminded that modification of the channel may require a US Army Corps of Engineers Section 404 permit.

Use of natural channels in the drainage system requires thoughtful planning, as they offer multiple-use opportunities. Certain criteria pertaining to artificial channels, such as freeboard depth and curvature, may not apply to natural channels in order to meet some of the multi-purpose objectives. Special consideration shall be given to transitions from “hard”to “soft” stabilization materials.

5.6 Grassed-Lined Channel Design Criteria

Grass-lined channels are encouraged when designing artificial channels. Advantages include: channel storage, lower velocities, provision of wildlife habitat, and aesthetic and recreational values. Design considerations include velocity, longitudinal slopes, roughness coefficients, depth, freeboard, curvature, cross-section shape, and channel lining material (vegetation and trickle channel considerations).

5.6.1 Design Velocity and Froude Number

It is recommended that the maximum normal depth velocity for grass-lined channels during the major design storm (i.e., 100-year) not exceed 7.0 feet per second for erosion-resistant soils and 5.0 per second for easily eroded soils. These velocity limitations assume a well-maintained, good stand of grass. The Froude number should not exceed 0.8 for erosion-resistant soils and 0.6 for easily eroded soils (UDFCD, 1990).

5.6.2 Longitudinal Slopes

Grass-lined channels should have longitudinal slopes of less than 1 percent, but will ultimately be dictated by velocity and Froude number considerations. In locations where the natural topography is steeper than desirable, drop structures should be implemented.

5.6.3 Roughness Coefficients

Table 5-6 provides guidance for roughness coefficients for grass-lined channels. The roughness coefficient for grass-lined channels depends on length and type of vegetation and flow depth. Roughness coefficients are smaller for higher flow depths due to the fact that at higher depths the grass will lay down to form a smoother bottom surface.

Table 5-6 Manning's Roughness Coefficients for Grass-Lined Channels - n
n - Value With Flow Depth Ranges

Grass Type	Length	0.0-1.5 ft	>3.0 ft
Bermuda grass, Buffalo grass, Kentucky bluegrass			
	Mowed to 2 inches	0.035	0.030
	Length 4 to 6 inches	0.040	0.030
Good stand any grass			
	Length of 12 inches	0.070	0.035
	Length of 24 inches	0.100	0.035
Fair stand any grass			
	Length of 12 inches	0.060	0.035
	Length of 24 inches	0.070	0.035

Source: UDFCD, 1990.

5.6.4 Freeboard

A minimum freeboard of 1 foot should be provided between the water surface and top of bank or the elevation of the lowest opening of adjacent structures. In some areas, localized overflow may be desirable for additional ponding/storage benefits.

Superelevation of the water surface should be determined at horizontal curves. An approximation of the superelevation can be made from the following equation:

$$h = V^2 Tw / g r_c \tag{5.4}$$

Where:
- h = superelevation (ft)
- V = velocity (ft/s)
- Tw = top width of channel (ft)
- g = acceleration due to gravity (32.2 ft/sec^2)
- r_c = centerline radius of curvature (ft)

5.6.5 Curvature

It is recommended that the centerline curves of channels have a radius of two to three times the design flow top width or at least 100 feet.

5.6.6 Cross-sections

Channel shape may be almost any type suitable to the site-specific conditions, and can be designed to meet multi-purpose uses, such as recreational needs and wildlife habitat. However, limitations to the design include the following:

- Side slopes should be 4 (horizontal) to 1 (vertical) or flatter. Slopes as steep as 3H:1V may be considered in areas where development already exists and there are right-of-way limitations.
- The bottom width should be designed to accommodate the hydraulic capacity of the cross-section, recognizing the limitations on velocity and depth. Width must be adequate to allow necessary maintenance (ASCE, 1992).
- Maintenance/access roads should be provided for along all major drainageways.

- Trickle channels or underdrain pipes should be provided on grass-lined channels to minimize erosion. As an alternative, low flow channels can be provided (low flow channels are particularly applicable for larger conveyances). Figure 5-3 shows typical cross-sections suitable for grass-lined channels. Trickle channels should be designed to carry base flow originating from lawn watering, low intensity rainfall events, and snow melt.

5.6.7 Grass Species

Seed mixes for the channel lining should be selected to be sturdy, easy to establish, and able to spread and develop a strong turf layer after establishment. A thick root structure is necessary to control weed growth and erosion. Seed mixes should meet all state and local seed regulations. Refer to Chapter 30 of the City of Lincoln Standard Specifications.

For additional guidance on seed mixes and seed rates the reader is referred to the local Natural Resources Conservation Service branch office and the LPSNRD. Table 5-7 provides suggested seed mixtures.

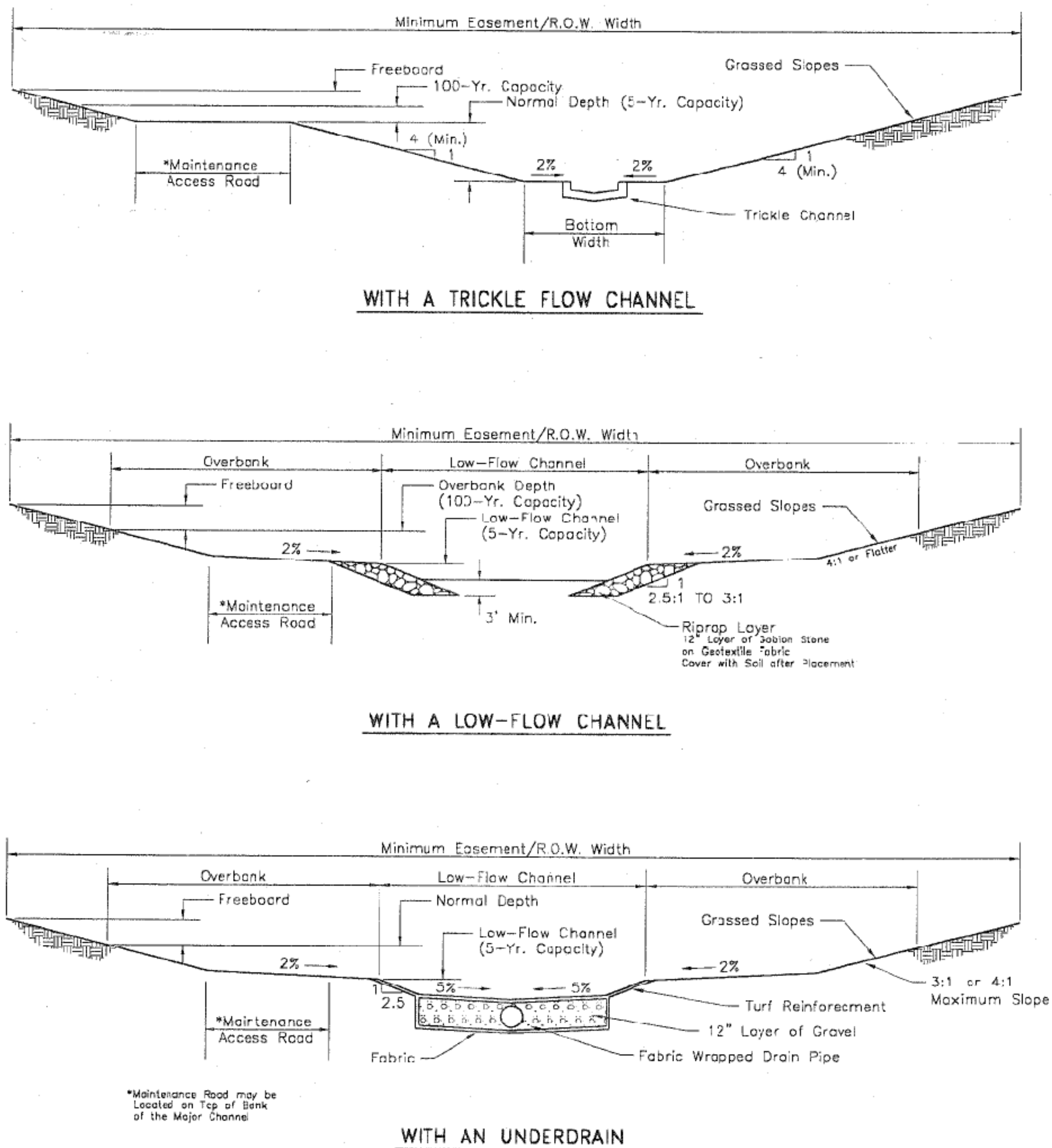


Figure 5-3 Typical Grass-Lined Channel Details

Source: UDFCD, 1990

Seeding Dates	Suggested Mixtures	Lbs. to Furnish 60 PLS/sq. ft. Per Acre	Loams, Clayloams, and Clays						Sands & Loamy Sand				Remarks
			A	B	C	D	E	F	A	D	E	F	
	Warm Season Dominant:												
October 1 - June 15	Big bluestem	4.0	X	0	-	-	X	-	X	-	X	-	For sands and loamy sands substitute sand bluestem for big bluestem, 1.8 lbs. of prairie sandreed for sideoats grama and 0.2 lb. PLS sand lovegrass for tall fescue.
	Sideoats grama	2.9	X	0	-	-	X	-	X	-	X	-	
	Switchgrass	0.7	X	0	-	-	X	-	X	-	X	-	
	Indiangrass	3.6	X	0	-	-	X	-	X	-	X	-	
	Tall fescue	2.1	X	0	-	-	X	-	X	-	X	-	
	Buffalograss (burs)	38.0	-	-	-	X	X	X	-	X	-	X	
	Blue grama	0.6	-	-	-	X	X	X	-	X	-	X	
	Buffalograss (burs)	32.3	0	-	-	X	X	X	-	X	-	X	
	Blue grama	0.3	0	-	-	X	X	X	-	X	-	X	
	Sideoats grama	2.7	0	-	-	X	X	X	-	X	-	X	
	Switchgrass	3.8	-	X	X	-	-	-	X	-	X	-	Wet areas
	Reed canarygrass	2.0	-	X	X	-	-	-	X	-	X	-	
	Cool-Season Dominant:												
August 15 - April 30	Smooth brome	14.4	X	0	-	-	X	-	X	-	0	-	Add 10 lbs. of western wheatgrass to replace 7.2 lbs. of brome or 3.6 lbs. of tall fescue.
	Switchgrass	1.7	X	0	-	-	X	-	X	-	0	-	
	Tall fescue	7.3	X	X	0	-	X	-	0	-	0	-	
	Switchgrass	2.4	X	X	0	-	X	-	0	-	0	-	
	Perennial ryegrass	5.2	-	-	-	X	-	X	-	X	-	X	Less than 5 years
	Alfalfa	10.8	-	-	-	X	-	X	-	X	-	X	
	Red clover	3.9	-	-	-	X	-	X	-	X	-	X	Substitute 0.6 lbs. PLS sand lovegrass to replace tall fescue for sands and loamy sands.
	Birdsfoot trefoil	1.9	-	-	-	X	-	X	-	X	-	X	
	Tall fescue	6.3	-	-	-	X	-	X	-	X	-	X	

KEY: X Best, 0 Fair, - Poor

A Dam, Diversion, Dike
B Channels
C Shoreline & Low Areas
D Heavy Traffic & Recreation
E Roadside
F Residential & Development Sites

Table 5-7 Suggested Seed Mixtures

Source: LPSNRD, 1994

5.7 Wetland Bottom Channel Design Criteria

Wetland bottom channels should be considered as the design approach in circumstances where existing wetland areas are affected or natural channels are modified. In fact, the USACE may mandate the use of wetland bottom vegetation in the channel design as mitigation for wetland damages elsewhere. Wetland bottom channels are in essence grass-lined channels, with the exception that wetland-type vegetation is encouraged in the channel bottom (this is usually accomplished by removing the trickle channel and slowing velocities). Increased water quality and habitat benefits are realized with the implementation of wetland bottom channels; however, they can become difficult to maintain (i.e., mow) and may be potential mosquito breeding areas.

Due to the abundant vegetation associated with wetland channels, flow conveyance will decrease and channel bottom agradation will increase. Consequently, channel cross-sections and right-of-way requirements will be larger than those associated with grass-lined channels.

The recommended procedures for wetland bottom channel design are quite similar to the design of grass-lined channels. For wetland channel design, the engineer must accommodate two flow roughness conditions to account for channel stability during a “new channel” condition and channel capacity during a “mature channel” condition.

5.7.1 Design Velocity

It is recommended that the maximum normal depth velocity for wetland bottom “new channel” conditions during the major design storm (i.e., 100-year) not exceed 7.0 feet per second for erosion resistant soils and 5.0 per second for easily eroded soils. The Froude number should not exceed 0.8 for erosion resistant soils and 0.6 for easily eroded soils under “new channel” conditions.

5.7.2 Longitudinal Slopes

The longitudinal slopes of wetland bottom channels should be dictated by velocity and Froude number considerations under “new channel” conditions.

5.7.3 Roughness Coefficients

As previously mentioned, wetland bottom channel design requires consideration of two roughness coefficient scenarios. To determine longitudinal slope and initial cross-section area, a “new channel” coefficient should be used. To determine design water surface, and final cross-section area, a “mature channel” coefficient should be used. The “mature channel” coefficient will likely be a composite coefficient. The following provides guidance for roughness coefficients for wetland bottom channels:

- New channel condition, use n = 0.030
- Mature channel condition, calculate a composite based on the following relation and Figure 5-4 (UDFCD 1990):

$$\mathbf{n_c = (n_0 p_0 + n_w p_w)/(p_0 + p_w)} \tag{5.5}$$

Where:
n_c = composite Manning’s n
n_0 = Manning’s n for areas above wetland (refer to Table 5.5)
n_w = Manning’s n for the wetland area (see Figure 5-4)
p_0 = wetted perimeter of channel above wetland area
p_w = wetted perimeter of wetland area (approximated as bottom width plus 10 feet)

5.7.4 Design Depth

As a preliminary design criteria, the maximum design depth of flow for the major storm runoff should not exceed 5.0 feet in areas of the channel cross-section outside the low flow channel area. Scour potential should also be analyzed when determining the design depth.

5.7.5 Freeboard

A minimum freeboard of 1 foot should be provided between the water surface and top of bank or the elevation of the lowest opening of adjacent structures. Freeboard should be determined based on the major storm water surface elevation under “mature channel” conditions.

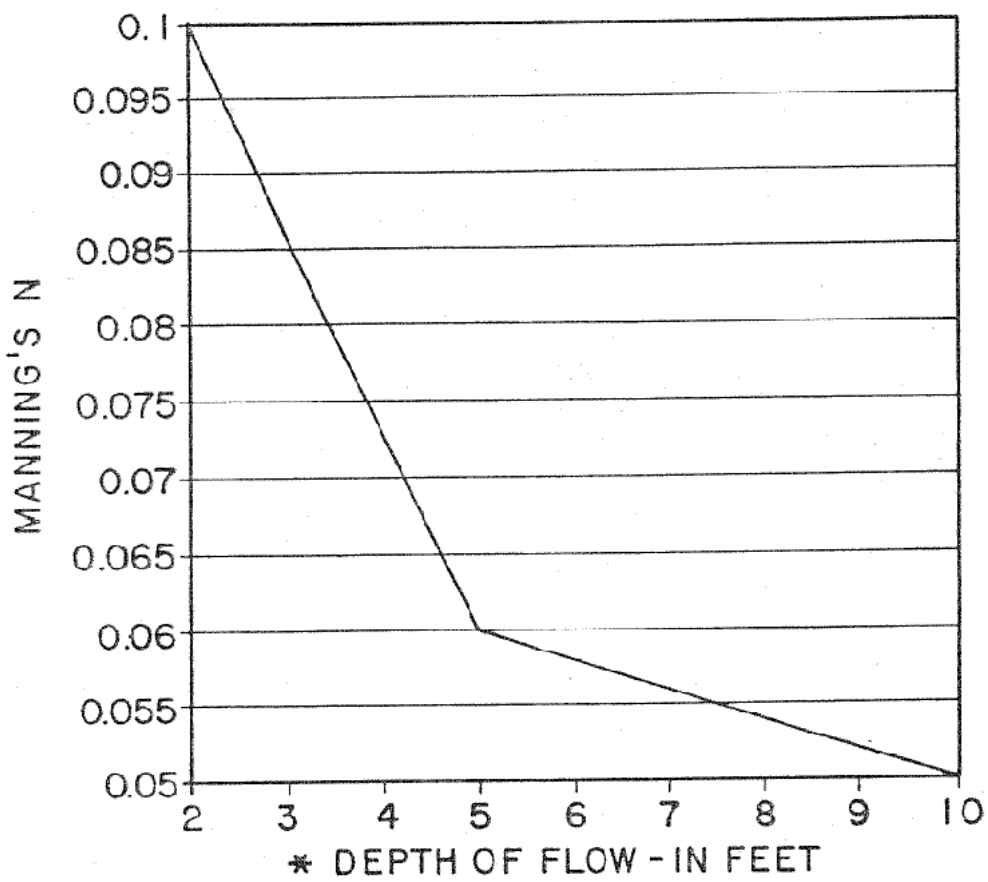
5.7.6 Curvature

It is recommended that the centerline curves of channels have a radius of two to three times the design flow top width or at least 100 feet.

5.7.7 Cross-sections

Channel shape may be almost any type suitable to the site-specific conditions, and can be designed to meet multi-purpose uses, such as recreational needs and wildlife habitat. However, limitations to the design include the following:

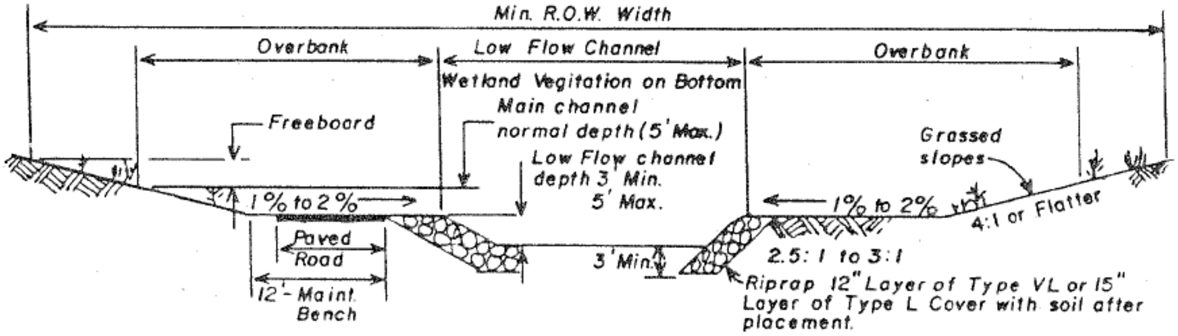
- Side slopes should be 4 (horizontal) to 1 (vertical) or flatter.
- It is recommended that the low flow channel be designed to convey the minor storm (i.e., 5- or 10-year storm) runoff.
- The bottom width should be designed to accommodate the hydraulic capacity of the cross-section, recognizing the limitations on velocity and depth. It is recommended that bottom widths not be less than 8.0 feet.
- Side slope banks of low flow channels should be lined with riprap or turf reinforcement material (at 2.5H:1V or 3H:1V) to minimize erosion. Figure 5-5 shows a typical cross-section suitable for wetland bottom channels.



* Use normal depth, ignoring all backwater effects

Figure 5-4 Depth of Flow vs. Manning's n for Wetland Bottom

Source: UDFCD, 1990



NOTES:

1) THIS SECTION IS REQUIRED FOR WETLAND BOTTOM CHANNELS

2) LOW FLOW CHANNEL MINIMUM CAPACITY TO BE NO LESS THAN GIVEN IN FIGURE 2-10 BUT SHOULD NOT EXCEED 5-YEAR FLOOD CAPACITY.

3) NORMAL DEPTH: FLOW DEPTH FOR THE 100-YEAR FLOW OUTSIDE THE LOW FLOW CHANNEL AREA SHALL NOT EXCEED 5-FEET

4) FREEBOARD: FREEBOARD TO BE A MINIMUM OF 1-FOOT TO TOP OF BANK OR TO LOWEST STRUCTURE FLOOR ELEVATION ADJACENT TO FLOODPLAIN

5) MAINTENANCE ACCESS ROAD: MINIMUM WIDTH OF THE FLAT SURFACE TO BE 12 FEET. LOCAL GOVERNMENT MAY REQUIRE THE ROAD TO BE PAVED. MAINTENANCE ROAD MAY BE LOCATED AS SHOWN ABOVE OR ON TOP OF MAIN CHANNEL BANK.

6) RIGHT-OF-WAY: MINIMUM WIDTH TO INCLUDE FREEBOARD AND MAINTENANCE ACCESS ROAD.

7) MAIN CHANNEL: FLOW IN EXCESS OF LOW FLOW CHANNEL SHALL BE CARRIED IN THE MAIN CHANNEL. THIS AREA MAY BE USED FOR RECREATION PURPOSES.

Figure 5-5 Typical Cross-Section of Wetland Bottom Channel

Source: UDFCD, 1990